# Noise Exposure May Diminish the Musician Advantage for Perceiving Speech in Noise

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**Objective:** Although numerous studies have shown that musicians have better speech perception in noise (SPIN) compared to nonmusicians, other studies have not replicated the "musician advantage for SPIN." One factor that has not been adequately addressed in previous studies is how musicians' SPIN is affected by routine exposure to high levels of sound. We hypothesized that such exposure diminishes the musician advantage for SPIN.

**Design:** Environmental sound levels were measured continuously for 1 week via body-worn noise dosimeters in 56 college students with diverse musical backgrounds and clinically normal pure-tone audiometric averages. SPIN was measured using the Quick Speech in Noise Test (QuickSIN). Multiple linear regression modeling was used to examine how music practice (years of playing a musical instrument) and routine noise exposure predict QuickSIN scores.

**Results:** Noise exposure and music practice were both significant predictors of QuickSIN, but they had opposing influences, with more years of music practice predicting better QuickSIN scores and greater routine noise exposure predicting worse QuickSIN scores. Moreover, mediation analysis suggests that noise exposure suppresses the relationship between music practice and QuickSIN scores.

**Conclusions:** Our findings suggest a beneficial relationship between music practice and SPIN that is suppressed by noise exposure.

**Key words:** Musicians, Noise exposure, Speech perception in noise.

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## INTRODUCTION

Communicating in noisy environments is universally difficult, although some individuals fare better than others. While hearing thresholds are one important factor that can affect speech intelligibility in noise, individual differences in hearing thresholds cannot explain the full range of performance observed on clinical measures of speech perception in noise (SPIN) (Anderson et al. 2013). Performance on such tests is known to depend on a multitude of auditory and nonauditory factors, including general cognition (Anderson et al. 2013; Boebinger et al. 2015), the listener's ability to use top-down knowledge to fill in acoustic details obscured by noise (Elliott 1995; Pichora-Fuller 2003), vocabulary knowledge (Anaya et al. 2016), the ability to store and recall linguistic item(s) from memory (Gordon-Salant & Fitzgibbons 1997), and the ability to attend to the target signal while inhibiting auditory distractors (Passow et al. 2012). In addition, lifestyle and experiential factors can also positively or negatively influence performance on SPIN tests (Van Engen & Bradlow 2007; Anderson et al. 2013; Skoe & Karayanidi 2018).

Playing a musical instrument is one experiential factor that has been identified as potentially positively influencing SPIN, although the extent to which music practice benefits SPIN is a subject of some controversy. We begin with a review of the literature on music practice and SPIN. (For a more in-depth, systematic review of the literature, including the neurophysiological correlates of SPIN, we refer the reader to Coffey et al. (2017)). Following our review of the literature, we offer a hypothesis to explain the mixed results, which we test in a sample of college students with clinically normal audiograms.

### Evidence For and Against Musical Training Having a Positive Influence on SPIN

Parbery-Clark et al. (2009) were the first to report a potential musician advantage for SPIN. They reported that classically trained adult instrumentalists who began training at an early age and practiced for at least 13 years outperformed those with less than three years of music practice on two clinical tests of SPIN, the Quick Speech in Noise Test (QuickSIN, Etymotic Research Inc.), and one but not all of the conditions of the Hearing in Noise Test (HINT; Nilsson et al. 1994). For the HINT, the musician advantage was observed when the speech and masker (speech-shaped noise) were spatially co-located (HINT-Front condition), but not for the two conditions where the speech and masker were spatially separated. In the same study, when the data were treated continuously, a correlational relationship emerged between total years of music practice and SPIN performance for the QuickSIN and the HINT-Front condition but not the spatially separated HINT conditions. Similarly, Ruggles et al. (2014) found a relationship between years of music practice and SPIN scores (QuickSIN and HINT) among musically trained young adults. Yet, as a group, the musically trained adults did not differ from nonmusicians on these clinical tests or on variants of these tests. Unlike Parbery-Clark et al. (2009), whose study participants were instrumentalists, Ruggles et al. (2014) included both instrumentalists and vocalists. This is noteworthy given new evidence suggesting that vocalists do not perform to the same level as instrumentalists on QuickSIN (Slater & Kraus 2016).

Another set of studies explored the degree to which musician advantages in SPIN are evident across the lifespan. Focusing on the younger end of the age spectrum, Strait et al. (2012) found that school-age children who began private instrumental training before age five and had at least 4 years of consistent practice (5 days/week) had superior performance on the HINT compared to demographically matched peers who were not musically active but were involved in other enrichment activities such as art classes. Examining the other end of the age spectrum, Zendel and Alain (2012), in their large cross-sectional study, provided evidence to suggest that musicians experience less age-related decline in QuickSIN scores than nonmusicians. Moreover, after controlling for age-related effects on the QuickSIN test, they found that better QuickSIN scores were associated with more

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musical activity per week (measured in hours/week), although an overall main effect of musicianship did not emerge for QuickSIN. In this study, the definition of musician was broad, and the sample also included amateur and professional musicians. In contrast to the Zendel and Alain (2012) study, a more recent study by Yeend et al. (2017) did not find an association between SPIN and music practice in their diverse sample of adults. However, one key difference between the studies is that the Yeend et al. (2017) study did not define music practice in terms of the total years of experience but instead asked participants to define the highest level of training that they had completed. Adopting more stringent criteria for defining a musician than either Zendel and Alain (2012) or Yeend et al. (2017), Parbery-Clark et al. (2011) focused on older adults with at least 40 years of active engagement in music making that began early in life, during preschool or early grammar school. This group of highly trained older adult musicians outperformed age-matched nonmusicians on QuickSIN, HINT, and Words in Noise. Thus, the discrepant findings across studies could partially be attributed to differences in how “musician” or “music practice” is being defined.

If music practice can benefit SPIN, as suggested by a large majority of the behavioral studies (16 of 18) in the systematic review by Coffey et al. (2017), which specific sensory and/or cognitive skills might be contributing to this advantage? Improved recognition of speech in noise for musicians could be due to their possession of heightened psychoacoustic abilities as the result of music practice (Yeend et al. 2017), including heightened frequency discrimination (Parbery-Clark et al. 2009; Ruggles et al. 2014; Boebinger et al. 2015; Madsen et al. 2017; Meha-Bettison et al. 2017) and temporal resolution (Mohamadkhani et al. 2010; Donai & Jennings 2016). To help isolate the factors that contribute to (potential) SPIN advantages in musicians, various studies have compared musicians to nonmusicians on versions of SPIN tests in which different acoustic features of the target speech and/or noise were manipulated. Fuller et al. (2014), for example, found that adult musicians performed slightly better than age-matched nonmusicians for word (but not sentence) identification tasks in which stimuli were processed through a cochlear implant simulation (Fuller et al. 2014). This SPIN advantage was attributed to musicians’ improved ability to discriminate vocal pitch cues in degraded speech stimuli. A more recent study found that while frequency discrimination was better for musicians than nonmusicians, musicians did not derive a greater benefit than did nonmusicians on a SPIN task when the fundamental frequency (F0) difference between the target and masker voices was increased (Madsen et al. 2017). In a similar study, Başkent and Gaudrain (2016) used a speech-on-speech design in which they manipulated two vocal characteristics of the competing sentence in a SPIN task: the F0 and the simulated vocal tract length. Using this paradigm, they found that musicians had higher speech-on-speech intelligibility scores than nonmusicians across all test conditions, which they interpreted as reflecting a generalized improvement in the auditory skills required for listening in noise that is not specific to voice processing (for a similar finding see Donai & Jennings 2016). In another study with a speech-on-speech paradigm, Swaminathan et al. (2015) presented masking stimuli from different spatial locations. They found that musicians, relative to nonmusicians, performed similarly when the target and masker were co-located, but the musicians showed a greater boost in performance, compared to the nonmusicians, when the target and masker were spatially separated. Yet, when Swaminathan et al. (2015) reduced the amount of informational masking by time-reversing the speech masker, a significant group difference appeared for the co-located condition but not the spatially separated conditions, with the musicians having lower speech recognition thresholds than the nonmusicians in the co-located condition. This is reminiscent of the findings by Parbery-Clark et al. (2009), in which a musician advantage emerged for the co-located condition but not the spatially separated conditions when the speech signal was energetically masked. Thus, this collection of studies indicates that the musician advantage for SPIN may depend on the amount of informational masking present and that musicians’ heightened psychoacoustic abilities may impart a greater advantage on some but not all SPIN test conditions.

While the focus of investigation has largely been on the auditory skills that might contribute to musician advantage for SPIN, a recent study by Anaya et al. (2016) examined the possibility that the musician advantage for processing degraded sensory input is not limited to the auditory modality but is instead domain-general. In support of this idea, the authors found long-term music training to be associated with enhanced acuity for a visual analog of SPIN in college musicians compared to nonmusicians, using a test that involved reading printed sentences where pixels were removed from each printed letter to create a visually fragmented stimulus (Anaya et al. 2016). This study also found a positive association between years of music practice and (auditory) SPIN in their musician group; however, while the group difference for the visual analog of SPIN was statistically different between musicians and nonmusicians, the group difference for the SPIN test was only marginally significant (Anaya et al. 2016). This study suggests that musicians may be relying on domain-general skills to process sensory input, in addition to reinforcing the idea that continuous-level data on musical training (e.g., years of playing a musical instrument) may be more sensitive to illuminating the association between music practice and SPIN than group comparisons that dichotomize participants into musicians and nonmusicians.

Another explanation for why musicians might have better SPIN is that musicians have better domain-general working memory and selective attention (Brochard et al. 2004; Rodrigues et al. 2013; Moradzadeh et al. 2015). By this account, musicians might have better SPIN because they are better able to attend to target speech amid background noise and then remember the target speech stimulus. Consistent with this interpretation, Parbery-Clark et al. (2009) found a correlation between auditory working memory and both QuickSIN and HINT performance. In addition, follow-up work to the Swaminathan et al. (2015) study performed by Clayton et al. (2016) found that performance on a spatial SPIN task related to performance on an auditory working memory task and selective (visual) attention task. If higher-level (nonauditory) cognitive factors mediate the SPIN advantage, this could explain why musicians and nonmusicians have been found to have equivalent speech-recognition thresholds across a variety of masking conditions (i.e., clear speech masker, spectrally rotated speech, speech–amplitude-modulated noise, and speech-spectrum-steady state noise) when they are matched with respect to higher-level factors, such as nonverbal IQ, auditory working memory, selective attention, and mental flexibility (Boebinger et al. 2015).

To summarize, while numerous studies have shown an association between musical training and SPIN, the effect of musical training does not always translate into a group difference when participants are categorized as musicians and nonmusicians. From these mixed findings, a debate has emerged about whether a musician advantage for SPIN exists, and if it does exist, what conditions bring it about. A variety of factors have previously been proposed to account for the mixed evidence that musical training benefits SPIN, including variation in how a "musician" is defined (e.g., instrumentalist, vocalist, professional, hobbyist, etc.), the extent to which the participant is currently active in musical activities, and inadequate control of linguistic factors and cognitive factors in study participants that may positively or negatively influence SPIN.

### The Negating Effects of Noise Exposure on SPIN

Another critical, but surprisingly underexplored, factor that could provide a further explanation of the mixed results linking musical training and SPIN is noise exposure. Musicians, especially those who play amplified music or practice and perform with large groups or in poor acoustic conditions, are regularly exposed to sound levels that place them at risk for noise-induced hearing loss (NIHL) (Miller 2007; Washnik et al. 2016; Tufts & Skoe 2018). Even before NIHL emerges on standard clinical measures of hearing, routine exposure to high levels of sound can compromise auditory processing (Hope et al. 2013; Liberman et al. 2016; Skoe & Tufts 2018). This leads us to hypothesize that routine noise exposure undermines the SPIN advantage accrued through music practice. The primary goal of the current study was to investigate this hypothesis by examining how music practice and noise exposure relate to SPIN in young adults with clinically normal hearing. To do so, we administered the QuickSIN test and obtained information about the participants' current noise exposure using a small body-worn sound level meter, called a noise dosimeter, that was worn for 1 week.

While the link between noise exposure and hearing loss is well-characterized (Rabinowitz 2000; Sliwinska-Kowalska & Davis 2012), the relationship between routine noise exposure and SPIN in individuals with clinically normal hearing has only recently received attention. In a small study from 2013, Hope et al. reported that military pilots with a history of high levels of occupational noise exposure had worse SPIN than an age-matched peer group of Royal Air Force administrators, who were not routinely exposed to occupational noise and who were audiometrically similar to the pilots with respect to the pure-tone average (PTA) of 0.5, 1, 2, and 4 kHz (Hope et al. 2013). This finding serves as preliminary evidence that routine noise exposure compromises SPIN, even when hearing threshold levels are accounted for, although we acknowledge that the 0.5–1–2–4 PTA may be insensitive to NIHL. In a more recent work, Liberman et al. (2016) found that young adults at risk for NIHL due to routine exposure to loud sounds had poorer speech recognition scores in noisy but not quiet conditions compared to an age-matched group that was considered to be at low risk for NIHL. In this case, the groups were audiometrically matched over the standard audiometric range (octave intervals from 0.25 to 8 kHz); however, there were statistically significant group differences in high-frequency audiometry, with the at-risk group having poorer high-frequency hearing than the low-risk group. Of note is that most, but not all, of the participants in their at-risk group were pursuing degrees in music performance; however, Liberman et al. (2016) did not examine the inter-relations between noise exposure, years of musical training, and SPIN. This motivates the current work, which uses multiple linear regression and mediation analysis to examine the relationships between QuickSIN, years of playing a musical instrument, noise exposure levels, and pure-tone audiometric averages. Like Liberman et al. (2016), we focus on college students but we expand on their methodology by using a dosimeter to objectively measure noise exposure over a 1-week period of the academic semester.

## MATERIALS AND METHODS

The study was approved by the Institutional Review Board at the University of Connecticut, and prior to starting the experiment, written consent was obtained from all participants. Participants received financial compensation for their participation in this weeklong study. In the laboratory, hearing thresholds and the QuickSIN test were all administered in a single-walled sound-attenuating chamber, prior to the dosimetry measurements. We adopted the US Department of Labor, Occupational Safety and Health Administration requirement of a 14-hour quiet period prior to performing a baseline hearing assessment in noise-exposed populations. This quiet period was mandated for all participants to minimize the likelihood of a temporary threshold shift due to recent noise exposure affecting the audiogram and QuickSIN test.

For all participants, dosimetry occurred during the academic semester, when curricular and extracurricular activities were underway, with the goal of generating a representative snapshot of noise exposure during the academic semester. Data collection was distributed across the academic semester, and we specifically avoided testing participants during the first 2 weeks of the semester, during the mid-semester break, or during finals week. We also factored in the performance schedules of the music ensemble participants during the semester to ensure that their testing occurred before the end of their performance schedule.

### Participants

Participants included 56 college students (13 males), aged 18–24 years, at the University of Connecticut with no history of neurological or otologic disorders. All participants were native speakers of American English, had clinically normal or near-normal QuickSIN scores, and had PTA audiometric thresholds <20 dB HL when averaged across 10 frequencies between 125 and 8000 Hz (see below).

Participants completed a questionnaire about their current and past musical activities. Across the group of 56 participants, all but eight had some experience playing a musical instrument or singing. We operationally defined the "years of playing a musical instrument" variable as the total number of years that the participant had played a musical instrument, with voice treated as an instrument. Across the entire participant sample, the total years of playing a musical instrument ranged from 0 to 17 years (mean = 7.80 years, SD = 5.16 years; Table 1) and the age that formal instrumental playing started ranged from 4 to 16 years (mean = 8.60 years, SD = 2.25). Two participants, whose

**TABLE 1. Noise exposure and musical history**

| A Noise Dose (%) | B Years | C Total Number of Current Groups | D Marching Band or Pep Band | E Instruments |
|---|---|---|---|---|
| Nonmusician | | | | |
| 1 | 1 | | | Recorder |
| 3 | 1 | | | Clarinet |
| 6 | 0 | | | |
| 6 | 0 | | | |
| 6 | 2 | | | Piano, Violin |
| 7 | 3 | | | Piano |
| 11 | 5 | | | Voice, Guitar |
| 11 | 6 | | | Saxophone |
| 15 | 3 | | | Violin |
| 17 | 0.5 | | | Trumpet |
| 19 | 0 | | | |
| 19 | 0 | | | |
| 19 | 0 | | | |
| 21 | 6 | | | Recorder, Guitar, Piano |
| 23 | 6 | | | Piano |
| 24 | 0 | | | |
| 27 | 0 | | | |
| 66 | 5 | | | Flute, Saxophone, Ukulele |
| 107 | 0 | | | |
| 150 | 0.5 | | | Keyboard |
| 294 | 2 | | | Guitar |
| Musician | | | | |
| 7 | 15 | 0 | | Piano, Guitar |
| 8 | 12 | 0 | | Voice, Guitar, Piano |
| 11 | 10 | 0 | | Cello, Flute |
| 11 | 14 | 0 | | Piano, Clarinet, Violin |
| 26 | 11 | 0 | | Violin, Flute |
| 26 | 17 | 0 | | Voice, Flute |
| 31 | 10 | 0 | | Piano, Trumpet, Marimba |
| 46 | 14 | 0 | | Piano, Harmonium, Voice, Flute |
| 54 | 9 | 0 | | Saxophone, Piano |
| 105 | 12 | 0 | | Drums, Voice |
| 771 | 8 | 0 | | Clarinet, Trumpet |
| 15 | 15 | 1 | | Trumpet, Piano*, Cello, Viola* |
| 30 | 10 | 1 | | Bassoon*, Clarinet, Oboe, Bass Clarinet, Tenor Saxophone, |
| 35 | 15 | 1 | | Voice*, Piccolo, Flute, Piano, Drums |
| 38 | 8 | 1 | | Voice*, Piano* |
| 41 | 9 | 2 | Y | Voice*, Color Guard in Marching Band* |
| 87 | 10 | 1 | Y | Flute*, Piccolo* |
| 97 | 8 | 1 | Y | Clarinet*, Piano |
| 175 | 9 | 2 | Y | Clarinet* |
| 178 | 12 | 1 | Y | Flute*, Trombone* |
| 237 | 14 | 3 | | Saxophone*, Violin, Piano |
| 248 | 11 | 1 | | Guitar*, Clarinet, Piano |
| 249 | 14 | 1 (music major) | | Voice*, Piano |
| 252 | 7 | 1 | Y | Alto Saxophone*, Voice |
| 345 | 11 | 2 | Y | Clarinet*, English Hand Bells |
| 373 | 11 | 1 | Y | Trumpet* |
| 540 | 14 | 3 | | Voice*, Flute, Violin, Piano, Guitar |
| 623 | 13 | 2 | Y | Trombone*, Flute, Hand Bells, Steel Drums, Voice* |
| 640 | 11 | 4 | Y | Clarinet*, Bassoon, Cymbals, Piano |
| 779 | 9 | 1 | Y | Trombone, Baritone*, Piano |
| 781 | 9 | 1 | Y | Saxophone* |
| 794 | 12 | 2 | Y | Trumpet*, Voice |
| 798 | 12 | 2 | Y | Mello*, Flute, Piano |
| 885 | 8 | 2 | Y | Baritone Horn*, Trombone, Piano |
| 902 | 12 | 1 | Y | Clarinet*, Piano |

*Participants are grouped based on the total years of musical training (Column B) into nonmusician (<7 years) and musician (≥7 years) groups. The musician group is further subdivided in this table based on whether they were active in a musical ensemble at the time they participated in the study, with the total number of ensembles listed in Column C. For each group, the participants are sorted based on Noise Dose (Column A), rounded to the nearest integer value. Column D indicates whether the participant was active in marching band or pep band, two ensembles that perform at loud sporting events on campus. For the participants with current and/or past musical experience, the instruments are listed in Column E in order of primary, secondary, (etc.) instrument.*

**Instruments that were being played at the time of study participation.*

primary instrument was voice at the time of testing, reported that they started singing before age 2 years, which is well before formal vocal training typically begins. In these two cases, Years of Playing a Musical Instrument was computed based on when the participant reported first starting formal music lessons on an instrument other than voice. For the purposes of performing group-level comparisons between "musicians" and "nonmusicians", the dataset was grouped based on the Years of Playing a Musical Instrument variable, with "musicians" being defined as having ≥7 years (n = 35) and "nonmusicians" defined as having <7 years of music training (n = 21; Table 1). This cutoff was selected because it represents the lowest number of years of music training among the subset of 24 participants who were currently active in music ensembles at the time of study enrollment. These 24 participants were active in the UConn pep band, marching band, wind ensemble, drumline, concert band, color guard, symphonic band, and/or one of several different choirs (Table 1). Unlike the students in the Liberman et al. (2016) study, most of the college students in our sample were pursuing degrees in fields outside of music (all but 1).

## Hearing Thresholds

In the laboratory, participants were screened using otoscopy and tympanometry to rule out outer- and middle ear pathology. Air-conduction thresholds were then obtained bilaterally at octave and semioctave frequencies (125, 250, 500, 1000, 1500, 2000, 3000, 4000, 6000, and 8000 Hz) using ER-2 insert earphones connected to a Grason-Stadler GSI 61 audiometer. Sheft et al. (2012) found that QuickSIN scores were strongly correlated with the average of the pure-tone thresholds at 0.5, 1.0, and 2.0 kHz (i.e., the PTA) in their investigation into the effects of age and hearing loss on QuickSIN, using a sample that ranged more broadly in age and hearing configuration than our sample. In addition to using the bilateral PTA of 0.5, 1.0, and 2.0 kHz (PTA 0.5–1–2) in our analyses, we incorporated the bilateral PTA of 3.0, 4.0, and 6.0 kHz (PTA 3–4–6), given that within the standard audiometric range, the indicators of NIHL often emerge first at these frequencies (Niskar et al. 2001).

## QuickSIN

The QuickSIN (Etymotic Research Inc.) was delivered from a CD via a GSI 61 audiometer through ER-2 insert earphones. The first four sentence lists from the corpus of 20 were presented. Each list contains six sentences, spoken by the same female voice. An example sentence is: The *square peg* will *settle* in the *round hole* (key words in italics). The sentences were presented at 70 dB HL, mixed with four-talker (three women and one man) babble. The starting level of the babble was 45 dB HL, increasing in 5-dB steps with each subsequent sentence presentation. Thus, the first sentence was presented with a signal to noise ratio (SNR) of 25 dB and the final (sixth) sentence is presented with an SNR of 0 dB.

One practice sentence list was given at the outset of testing to provide an opportunity for the participant to become familiarized with the test procedures. During the test, participants were instructed to repeat back each sentence immediately after it was played, and the number of key words correctly repeated was recorded, with each sentence containing five key words. The score for each sentence list was reported as an "SNR Loss", derived by subtracting the total number of correct key words (out of a possible 30) for that list from 25.5. The lower the SNR Loss, the better the performance, with the lowest (i.e., best) possible score for each list being −4.5 dB. The SNR Loss was averaged across the four sentence lists to compute the final QuickSIN score used in the statistical analyses. SNR Loss ≤2 dB is considered clinically normal based on data provided by the test developers. QuickSIN scores in the current sample ranged between −1.25 and 2.25 dB SNR loss, with four participants scoring above 2 dB SNR loss.

## Noise Dosimetry

At the end of the test session in the laboratory, participants were trained to use a noise dosimeter (ER-200DW8 personal noise dosimeter; Etymotic, Inc.) and to manually record their daily activities into an activity logbook (Tufts & Skoe 2018). Participants were instructed to wear the dosimeter on their clothing, near the ear, and to leave the microphone inlet uncovered. When sleeping or showering, or during activities when the device might be damaged (e.g., sports), participants were told they could remove the dosimeter but to keep it nearby if possible.

Before the participant left the laboratory, the experimenter turned on the dosimeter and immediately recorded the time of day. Participants were instructed to contact the research team if any issues relating to the dosimeter arose during the week. The turnoff button was disabled so that participants could not accidentally shut off the dosimeter. After seven full days, they returned to the laboratory to hand in the dosimeter and the daily activity log and to receive compensation for their participation in the study.

The dosimeters were configured to an 85-dBA criterion level and 3-dB exchange rate, in conformance with the National Institute for Occupational Safety and Health criteria (NIOSH, 1998), and a 75-dBA threshold. The measurement period was set to seven consecutive 24-hour days. During the measurement period, the dosimeters obtained dose values every 220 msec and summed these values over 3.75-minute increments to facilitate data visualization and analysis. The calibration of all dosimeters was periodically checked during the data collection period to ensure that the instruments were operating properly. This was done by generating a continuous 1000-Hz narrowband signal at a nominal level of 90 dB SPL in an Audioscan Verifit test box and measuring its level with a calibrated Type 1 sound level meter (Larson-Davis 824) and with each dosimeter in "Quick-Check" mode. For each measurement, the microphone of the device was positioned at the same location in the test box. Measured dosimeter levels fell within 2.5 dB of the mean of three sound-level meter measurements.

Dosimetry data were downloaded to .txt files, one per participant, using the ER200D Utility Suite software (version 4.04). The data were then processed individually for each participant using an in-house MATLAB routine (release 2016a, The Mathworks, Inc.) that separated the data by date, using the dosimeter start time recorded by the investigator. The noise dose for each measurement date was calculated using NIOSH procedures, and doses were averaged across days. This week-long average serves as our measure of "Noise Exposure." Our participant sample displayed a wide range of Noise Exposures from 1 to 902% average noise dose (Figs. 1 and 2). The

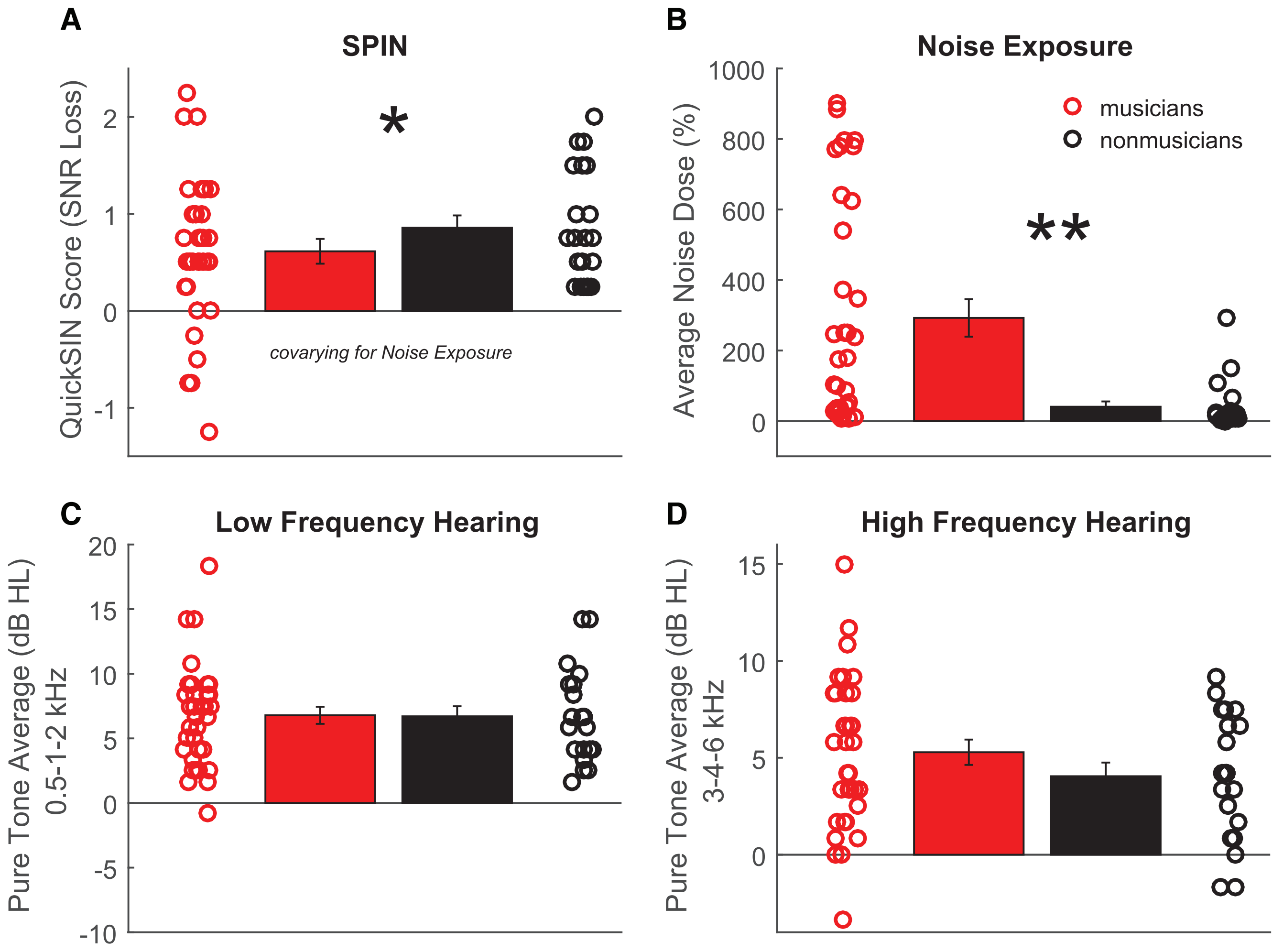

Fig. 1. Comparisons between the musician (red) and nonmusician (black) groups on (A) Quick Speech in Noise Test (QuickSIN), (B) Noise Exposure, and (C) Pure-tone average (PTA) threshold for 0.5, 1, and 2 kHz and (D) PTA threshold for 3, 4, and 6 kHz. In each panel, group means are plotted for each test, with error bars representing one standard error of the mean. One-dimensional scatter plots show the distribution of scores across groups. $^*p < 0.05$, $^{**}p \leq 0.01$. SNR, signal to noise ratio.

participants with the highest exposures were predominantly, though not exclusively, individuals who were active in large music ensembles at the time of testing. Note that in reference to the dosimeter, noise refers to exposure to high-intensity sound, whereas for QuickSIN, noise refers to a distracting background sound that energetically and informationally masks the target signal.

### Statistical Analysis

The Kolmogorov–Smirnov test was used to test for normality of the dependent variables. All variables except the Noise Exposure measure met the condition of normality. The Noise Exposure measure was log-transformed so that it would conform to normality, and the statistical analyses were carried out on the transformed data. Statistical analyses were performed in SPSS (version 24, IBM, Inc.) or, when specifically noted, in the R programming language (version 3.3.1). Relations among variables were first examined using Pearson correlations. This was followed by multiple linear regression. Multiple linear regression was used to model the relationship between QuickSIN SNR Loss score (the response variable) and two explanatory variables (Years of Playing a Musical Instrument, and Noise Exposure). $R^2$ values (both adjusted and unadjusted) are reported.

Partial correlations were performed in SPSS to measure the association between two variables after adjusting for the influence of an additional variable. To generate a partial correlation plot between QuickSIN and Years of Playing a Musical Instrument that adjusts for the influence of Noise Exposure on both variables (Fig. 2C), we did the following: (1) we computed the standardized residuals (i.e., the difference between the predicted and response variables) when regressing QuickSIN against Noise Exposure, (2) we computed the standardized residuals when regressing Years of Musical Training against Noise Exposure, and then (3) we plotted two residuals against each other. The same process was repeated to create a partial correlation plot between QuickSIN and Noise Exposure that adjusts for the influence of Years of Playing a Musical Instrument (Fig. 2D).

We tested for an interaction between Noise Exposure and Years of Playing a Musical Instrument on QuickSIN SNR Loss score, as part of a moderator regression analysis performed in

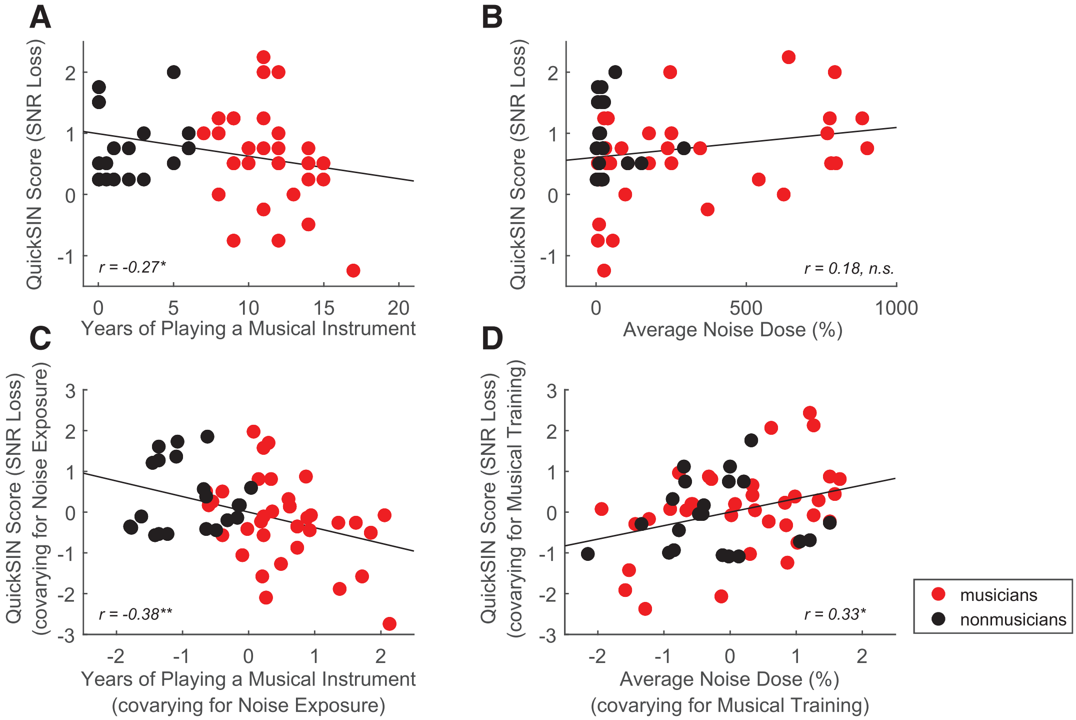

Fig. 2. Relationships between music training and Quick Speech in Noise Test (QuickSIN) scores (A, C) and Noise Exposure and QuickSIN scores (B, D). Top, Scatterplots illustrating the relationship between Years of Musical Training and QuickSIN signal to noise ratio (SNR) Loss scores (A) and the relationship between Noise Exposure and QuickSIN SNR Loss scores (B). Bottom, Partial correlation plots between QuickSIN SNR Loss scores and Years of Playing a Musical Instrument, controlling for Noise Exposure (C) and between QuickSIN SNR Loss scores and Noise Exposure, controlling for Years of Playing a Musical Instrument (D). Note that for panels C and D, abscissa and ordinate reflect standardized residual scores. To help visualize the trends in the data, the data point for each participant is color-coded to depict their group membership in Figure 1 (red = musicians, black = nonmusicians). $^*p < 0.05$, $^{**}p <= 0.01$.

SPSS. Finally, we tested whether Noise Exposure has a suppressive effect on the relationship between Years of Playing a Musical Instrument and QuickSIN SNR Loss score, in the R programming language (version 3.3.1) using R Studio version 1.1.423 (R Core Team, Boston, MA) via the Mediation package. A suppression effect, also referred to as an inconsistent mediation, is present when the direct and mediated effects of the predictor variable (Years of Playing a Musical Instrument) on the dependent variable (QuickSIN SNR Loss score) have opposite signs (MacKinnon et al. 2000, 2007). The indirect (suppressive) effect was tested using a bootstrap estimation approach with 10,000 samples (Hayes & Scharkow 2013).

## RESULTS

### Group Comparisons

The nonmusician group had a mean noise dose of 41% (SD = 69), with a range of 1 to 294%. By contrast, the musician group had a mean noise dose of 293% (SD = 315), with a range of 7 to 902%, a statistically significant difference compared to the nonmusician group, $F(1,55) = 12.96$, $p < 0.01$ (Fig. 1B).

Noise doses >100% are associated with increased risk for hearing loss (NIOSH, 1998). The mean noise dose of the musicians (293%) suggests that, on average, they are at greater risk of NIHL than are the nonmusicians (mean dose = 41%), although it is not possible to predict a given individual's likelihood of developing NIHL from population data. Examination of the activity books filled out by the participants in conjunction with the dosimetry data revealed that high noise levels were most often associated with social activities for the nonmusicians and with both music and social activities for the musicians. Our sample size did not permit a meaningful comparison of doses as a function of instrument(s) played for the musicians (Table 1). We note, however, that the four musicians with low noise doses (<50%) played relatively quiet instruments at the time of study participation (voice, piano, bassoon). Moreover, of these four, only one was involved in more than one musical ensemble; this participant was active in a choir but also participated in color guard, a nonmusical section of the UConn Marching band that uses visual flags, mock rifles, and other equipment to move rhythmically to the music.

Despite being at greater risk for NIHL, the musician group did not differ significantly from the nonmusician group with respect to either the lower-frequency (0.5, 1.0, and 2.0 kHz; Fig. 1C) or the higher-frequency (3.0, 4.0, and 6.0 kHz; Fig. 1D) PTA ($F(1,55) = 0.01$, $p = 0.94$; $F(1,55) = 1.50$, $p = 0.23$, respectively). For the lower-frequency range, the musician group had a PTA of 6.78 dB HL (SD = 3.92) and the nonmusician group had a mean PTA of 6.71 dB HL (SD = 3.55; Fig. 1C). For the higher-frequency range, the musician group had a PTA of 5.28 dB HL (SD = 3.86), compared to 4.04 dB HL (SD = 3.23) for the nonmusician group (Fig. 1D). Given the typically gradual progression of NIHL over time, the relative youth of the participant sample, and the imperfect relationship between noise dose and lifetime noise exposure, this finding is not surprising (Jin et al. 2013).

For QuickSIN, the nonmusician group had a mean SNR Loss score of 0.86 (SD = 0.58), with a range of 0.25 to 2.00. For the musician group, the mean was 0.61 (SD = 0.75), with a range of −1.25 to 2.25. The QuickSIN SNR Loss scores were not statistically different between the two groups, $F(1,55) = 1.59$, $p = 0.21$, until Noise Exposure was added as a covariate $F(1,53) = 6.17$, $p = 0.02$ (Fig. 1A).

## Correlations Among Variables

The next set of analyses treated musical training as a continuous variable, using the Years of Playing a Musical Instrument variable. To explore the inter-relations among variables, pairwise correlations were performed between QuickSIN SNR Loss scores, PTAs, Noise Exposure, and Years of Playing a Musical Instrument. We begin with presenting the correlations between PTAs and the other variables. The relation between QuickSIN SNR Loss scores and PTA-0.5–1–2 kHz was not statistically significant (r = 0.01, p = 0.93), nor was the relation with the PTA-3–4–6 kHz ($r = −0.13$, $p = 0.35$) significant. With respect to Noise Exposure, significant relations were not found with either PTA metric ($r = 0.04, p = 0.77$; $r = 0.14, p = 0.3$, respectively for PTA-0.5–1–2 and PTA-3–4–6 kHz). Likewise, for Years of Playing a Musical Instrument, significant relations did not emerge with either PTA ($r = 0.04$, $p = 0.77$; $r = 0.14$, $p = 0.34$, respectively for PTA-0.5–1–2 and PTA-3–4–6 kHz).

Next, we consider the relations between Years of Playing a Musical Instrument and the other variables. The relationship between Years of Playing a Musical Instrument and QuickSIN SNR Loss scores was found to be statistically significant, with more years of music practice being associated with better (lower) SPIN scores ($r = −0.27, p = 0.04$; Fig. 2A). However, the relationships between QuickSIN scores and other measures of music practice were not significant (years since playing a musical instrument, $r = −0.02$, $p = 0.87$; age that instrumental playing started, $r = 0.16$, $p = 0.29$).

There was also a significant relationship between Years of Playing a Musical Instrument and Noise Exposure ($r = 0.41$, $p < 0.002$), with more years of playing a musical instrument associated with higher levels of noise exposure. The relationship between Noise Exposure and Years of Playing a Musical Instrument can be explained as follows: The average age for starting musical training in our dataset was 8.6 years, which is consistent with when most children begin playing a musical instrument in school in the United States (Steinel 1990). Individuals who begin musical activities as school-age children and continue with musical activities in college music ensembles will generally have more years of playing a musical instrument than those who do not continue playing into college. Since participation in college music ensembles was associated with higher levels of exposure, it follows that participants with more years of playing an instrument generally had higher levels of exposure.

Consistent with the possibility that noise exposure suppresses the relationship between SPIN and musical training, the relationship between QuickSIN SNR Loss scores and Years of Playing a Musical Instrument was stronger when Noise Exposure was added as a covariate ($r = −0.38$, $p = 0.004$; Fig. 2C). Note, however, that the pairwise correlation between QuickSIN SNR Loss scores and Noise Exposure was not statistically significant ($r = 0.18$, $p = 0.18$; Fig. 2B) until Years of Playing a Musical Instrument was added as a covariate ($r = 0.33, p = 0.01$; Fig. 2D).

To examine how Years of Playing a Musical Instrument and Noise Exposure collectively and independently predict QuickSIN scores, multiple linear regression analysis was performed, using Years of Playing a Musical Instrument and Noise Exposure as the predictor variables. A significant regression model emerged ($F(2,53) = 5.9$, $p = 0.01$), with an $R^2$ of 0.17 and an adjusted $R^2$ of 0.14. Moreover, both measures were found to be independent, significant predictors of QuickSIN SNR Loss scores. Consistent with our predictions, the regression analysis indicated that Years of Playing a Musical Instrument was associated with better QuickSIN SNR Loss scores (standardized coefficients $\beta = −0.41$, $t = −3.02$, $p = 0.004$) but Noise Exposure was associated with worse SNR Loss scores ($\beta = 0.35$, $t = 2.5$, $p = 0.01$). We then tested a reduced model, containing only Years of Playing a Musical Instrument as a predictor. This reduced model, with an $R$ of 0.26 and an adjusted $R^2$ of 0.05 ($F(1,54) = 4.00$, $p = 0.05$), had a significantly lower $R^2$ than the model that included Noise Exposure as the second predictor (adjusted $R^2$ change = 0.13, $F(1,53) = 5.77$, $p = 0.02$). Thus, Noise Exposure is a significant, additional predictor of QuickSIN SNR Loss scores beyond the predictive value of Years of Playing a Musical Instrument alone. For all models tested, the variance inflation factor was <2, suggesting that there were no indications of multicollinearity.

## Moderation and Mediation Analysis

Moderation analysis was performed to evaluate whether Noise Exposure and Years of Playing a Musical Instrument interact in predicting QuickSIN SNR Loss scores. A significant interaction would indicate that the strength of the relationship between Years of Playing a Musical Instrument and QuickSIN is different for lower compared to higher values of Noise Exposure. We did not find evidence for an interaction. Using a stepwise regression approach, we found that adding the interaction term to the regression model did not increase the variance explained for QuickSIN SNR Loss scores ($R^2$ change = 0.01, $F(1, 51) = 0.524$, $p = 0.47$) nor was the beta weight of the interaction term significant (standardized coefficients $\beta = 0.14$, $t = 1.04$, $p = 0.30$).

Next, we performed a mediation analysis. To test whether noise exposure has a suppressive effect on the relationship between years of playing a musical instrument and QuickSIN, we tested an “inconsistent” mediation model in which Years of Playing a Musical instrument was the independent (predictor) variable, QuickSIN SNR Loss was the dependent variable, and Noise Exposure was the suppressor variable. When Noise Exposure was included as a mediating variable, the direct effect between Years of Playing a Musical Instrument is stronger ($b = −0.06$, 95% confidence interval [CI] = −0.10 to −0.02, $p = 0.003$) than the total effect (i.e., model without the suppressor; $b = −0.04$, 95% CI = −0.07 to 0.00, $p = 0.05$). Consistent with Noise Exposure acting as a suppressor variable, the indirect path of the mediation model has an opposite sign ($b = 0.019$, 95% CI = 0.003 to 0.04, $p = 0.01$) from the direct path ($b = −0.06$). Thus, the mediation analysis suggests that musical training affects SPIN abilities directly and indirectly. Through

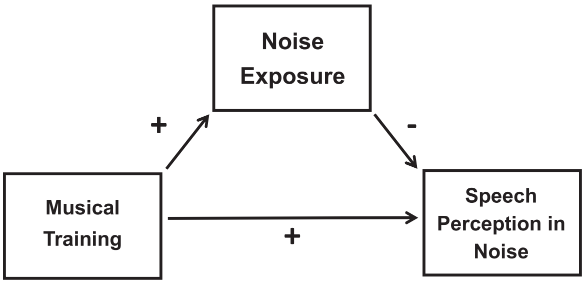

Fig. 3. Schematic representing the direct and indirect effects of musical training on speech perception in noise (SPIN). Mediation analysis suggests that musical training affects SPIN abilities directly and indirectly. Through the direct path, it has a beneficial effect on SPIN. But through the indirect, mediated path of noise exposure, musical training results in worse SPIN performance.

the direct path, it has a beneficial effect on SPIN. However, through the indirect (mediated) path of Noise Exposure, musical training results in worse QuickSIN performance (Fig. 3).

## DISCUSSION

Despite the well-recognized hearing hazards of music making, the combined effect of music practice and noise exposure on speech perception in background noise is understudied. This motivated us to examine the relations between music practice, noise exposure, and SPIN. Our analysis revealed three key findings: first, both variables—total years of playing a musical instrument and noise exposure—were significant predictors of SPIN, after controlling for the confounding influence of the other variable. Consistent with this, the group-level comparison did not reveal a musician advantage for SPIN, until noise exposure was added as a covariate. Second, we found that total years of playing a musical instrument and noise exposure have opposing relationships with SPIN, with more music practice being associated with better QuickSIN scores and more noise exposure being associated with worse QuickSIN scores. Third, years of playing a musical instrument had both a direct and indirect influence on SPIN, with the indirect pathway being mediated by noise exposure. Importantly, noise exposure was found to be a suppressor variable on the mediating relationship between musical training and SPIN, suggesting that more years of musical training can increase the likelihood of higher levels of noise exposure, which in turn can yield lower SPIN abilities. The current study, thus, provides evidence to support our hypothesis that noise exposure may undercut the beneficial influences that music practice can have on SPIN. When taken in the context of the larger literature on SPIN in musicians, our findings offer a new explanation for why the positive effect of music practice on SPIN seen in some studies was not observed in others, given that none of the previous studies used objective measures of noise exposure to account for the potentially negating influence of noise exposure on SPIN (Ruggles et al. 2014; Boebinger et al. 2015; Madsen et al. 2017; Yeend et al. 2017).

Using a body-worn dosimeter, we measured noise exposure in college students continuously over a week (seven consecutive days) during an academic semester. We compared QuickSIN scores and noise exposure, with the presumption that the observed noise doses were generally representative of the participants' typical noise exposure patterns during the academic year. When interpreting our study outcomes, two important methodological details must be considered: (1) for all participants, all auditory testing (including QuickSIN) took place following a 14-hour quiet period to minimize potential contamination from a temporary threshold shift, which would be a concern for participants who regularly engage in loud activities, and (2) the noise dosimeters were turned on only after all auditory testing had been completed. Thus, poorer performance on the QuickSIN test cannot be interpreted as the direct result of noise exposure measured as part of the study, nor is it likely to be the direct result of noise exposure occurring immediately prior to testing. When interpreting our findings, it should also be noted that the QuickSIN scores were predominately in the clinically normal range, with only a small number of data points (4 out of 56) falling at the upper end of the normal range. Thus, we do not observe any functional (i.e., clinically significant) SPIN deficits, but rather a statistically significant decrease in performance within the normal range, in a young adult population whose weekly noise doses ranged from 1 to 902%.

A strength of our study is that we have noise dosimetry on all of our participants over the course of one week, and this dosimetry data has given us new insight into the relationship between routine noise exposure and SPIN. However, methodological limitations of our study should be acknowledged. First, our noise dosimetry protocol does not capture sound exposure through headphones or earphones, and therefore, we likely underestimate the total noise exposure. Second, we did not formally assess whether the presence of the dosimeters influenced participants' behavior in ways that could have impacted their noise exposure. However, we explicitly instructed the participants to go about all of their normal activities during the measurement period, and we saw no evidence in the activity books suggesting they did otherwise. Third, we did not have the equipment needed to obtain extended high frequency audiometric thresholds above 8 kHz, and the potential impact of extended high frequency hearing on SPIN is, therefore, unknown in our study sample. This is noteworthy given that there have been repeated demonstrations of high frequency hearing loss in noise-exposed populations in recent studies (Liberman et al. 2016; Grose et al. 2017; Prendergast et al. 2017; Yeend et al. 2017)

Another limitation is that we cannot validate whether the dosimetry measurements are representative of longer-term or lifetime noise exposure in our participants. This prevents us from making any conclusive statements about the relationship between SPIN and lifetime noise exposure in our participants. Recent studies investigating SPIN and metrics of lifetime noise exposure have found no relation between the two and no evidence that a SPIN impairment is associated with noise exposure (Yeend et al. 2017; Guest et al. 2018). This is not completely unlike the current study where the relation between QuickSIN and noise dosimetry was not statistically significant, until years of playing a musical instrument was added as a covariate. As with the present study, Yeend et al. (2017) explored the influences of music practice and noise exposure on SPIN, but they focused on lifetime noise exposure, as estimated from responses to an online survey. As expected, the professional musicians in their sample had greater estimated lifetime sound exposure than the nonmusicians. However, across the sample, estimated lifetime noise exposure was not predictive of SPIN nor was music practice predictive of SPIN. In other words, neither a benefit of music practice nor a detriment of lifetime noise exposure on SPIN was observed.

While the Yeend et al. (2017) study addressed a similar question as the current study, there is little overlap in methodology. First, unlike the current study where the study sample was limited to young adult college students with clinically normal hearing, Yeend et al. tested a larger, more diverse sample (aged 30–57 years), one-third of whom had mild hearing loss (the rest had clinically normal hearing, i.e., thresholds ≤20 dB HL at 0.25–6 kHz). In addition, their study sample included professional musicians, amateur musicians, and nonmusicians, whereas ours included no professional musicians. Second, in the Yeend et al. (2017) study, music practice was not defined in terms of years of experience. Instead, music practice was operationalized using the highest level of schooling at which the participant had received formal training, with the levels being: primary, secondary, tertiary, post-secondary, or no training (Chin & Rickard 2012). This measure (at least, how it was described by Yeend et al. (2017)) is categorical and therefore may be poorly suited to capture the relationships between music practice, noise exposure, and SPIN. These methodological and demographic differences complicate our ability to draw conclusions across the two studies.

Another factor that must be considered when examining differences in the study outcomes is that the two studies used different SPIN tests: QuickSIN (current study) and one subset of the Listening in Spatialized Noise–Sentences Test (LiSN-S; Cameron et al. 2011) in the Yeend et al. (2017) study. These two tests differ from each other on multiple dimensions, with the QuickSIN arguably being a more difficult test. In QuickSIN, the target speech and background babble are spatially co-located. By contrast, in the LiSN-S subtest, the target speech (a woman's voice) is spatially separated by 90 degrees from the distractors, with the distractors being two children's stories spoken by female voices that loop continuously throughout the test. The LiSN-S test also uses simpler vocabulary and syntactic structure than QuickSIN for both the target and distractor speech. Unlike QuickSIN, the SNR is changed adaptively, and the listener is cued (using a 1000-Hz tone burst) that the next sentence is about to begin. While QuickSIN has been used previously to examine the influence of musicianship on SPIN (e.g., Parbery-Clark et al. 2009, 2012; Zendel and Alain 2012; Ruggles et al. 2014), we are aware of only one other study to have used the LiSN-S for this purpose (Meha-Bettison et al. 2018). In that study, Meha-Bettison et al. (2018) administered all four subtests of the LiSN-S test to a small group of professional musicians and nonmusicians and found that the professional musicians outperformed the nonmusicians on only one of the subtests, the most challenging subtest. In this most challenging subtest of the LiSN-S test, which was not part of the test battery in the Yeend et al. (2017) study, the target sentence and distractor stories are spoken by the same voice. Thus, it is possible that no musician advantage was seen by Yeend et al. (2017) because their measure of SPIN was not sufficiently challenging to reveal an advantage.

Finally, and perhaps most critically, differences in the noise exposure measures used in the two studies could also account for the disparate findings. Yeend et al. (2017) used a survey-based estimate of lifetime noise exposure, whereas we used an objective measurement of current noise exposure over a single representative week. Each measure has intrinsic limitations and each provides at best an incomplete representation of noise exposure. Estimating lifetime noise exposure from a survey could provide a general picture of the number of years and/or types of exposures, but, even in a clinical setting, such measures are taken with a grain of salt, because they are subject to errors of recall, loudness judgment, and so on. A one-week objective measurement, assuming it was done correctly, provides quantifiable evidence of the amount of noise exposure but cannot be assumed to be representative of an individual's lifetime exposure.

Without dissecting each study further, it should be clear from the discussion above that multiple possible explanations exist for why Yeend et al. (2017) came to a different conclusion regarding the effects of music practice and noise exposure on SPIN than we did. Alternatively, it could be argued that our study outcomes are not, in fact, fundamentally different from those reported by Yeend et al. (2017), given that we did not observe any clinically significant SPIN deficits in our participant sample. Nevertheless, to further explicate the relation between noise exposure and SPIN, there would be value in using a test protocol that includes multiple measures of SPIN (e.g., QuickSIN and LiSN-S) and multiple measures of noise exposure, including dosimetry to assess current noise exposure levels, well-vetted survey-based approaches to estimate lifetime noise exposure, and extended high-frequency audiometry.

## CONCLUSIONS

The results from this study suggest that noise exposure and music practice can both influence how well a listener can understand speech in a noisy background, and that noise exposure can suppress the positive effects of music practice on SPIN. Our study, thus, establishes the need to consider noise exposure when investigating SPIN in musicians. However, a limitation of the current investigation is that we did not evaluate the host of other variables that may affect SPIN performance and presumably covary with music practice, including various measures of cognition and language ability, socioeconomic status, as well as other auditory abilities (Anderson et al. 2013; Le Prell et al. 2013; Boebinger et al. 2015; Anaya et al. 2016; Reetzke et al. 2016). Future studies should consider using structural equation modeling and other multivariate statistical techniques to elucidate the degree to which clinical measures of SPIN can be predicted from a broader constellation of auditory and nonauditory factors (Anderson et al. 2013), including measures that better characterize lifetime noise exposure.

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